

REPORT DOCUMENTATION PAGE			Form Approved OMB NO. 0704-0188		
<p>The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA, 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.</p> <p>PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.</p>					
1. REPORT DATE (DD-MM-YYYY) 01-03-2016		2. REPORT TYPE Final Report		3. DATES COVERED (From - To) 1-Jul-2014 - 31-Mar-2015	
4. TITLE AND SUBTITLE Final Report: STIR: Novel Electronic States by Gating Strongly Correlated Materials			5a. CONTRACT NUMBER W911NF-14-1-0375		
			5b. GRANT NUMBER		
			5c. PROGRAM ELEMENT NUMBER 611102		
6. AUTHORS David Goldhaber-Gordon			5d. PROJECT NUMBER		
			5e. TASK NUMBER		
			5f. WORK UNIT NUMBER		
7. PERFORMING ORGANIZATION NAMES AND ADDRESSES Stanford University Office of Sponsored Research 3160 Porter Drive, Suite 100 Palo Alto, CA 94304 -8445			8. PERFORMING ORGANIZATION REPORT NUMBER		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS (ES) U.S. Army Research Office P.O. Box 12211 Research Triangle Park, NC 27709-2211			10. SPONSOR/MONITOR'S ACRONYM(S) ARO		
			11. SPONSOR/MONITOR'S REPORT NUMBER(S) 65600-PH-II.1		
12. DISTRIBUTION AVAILABILITY STATEMENT Approved for Public Release; Distribution Unlimited					
13. SUPPLEMENTARY NOTES The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.					
14. ABSTRACT Electrostatically modulating the carrier density of semiconductors, where the physics is relatively simple and well-understood, has long been the foundation for electronic devices. What if we could apply these techniques to a much broader range of materials? This short grant aimed at demonstrating such large potential modulations in correlated electron materials using a technique known as electrolyte gating. This plan built on my group's recent demonstration of electrolyte gating in Strontium Titanate, using an atomically thin hexagonal Boron Nitride barrier to prevent disorder and chemical modification of the surface of the Strontium Titanate during the electrolyte gating.					
15. SUBJECT TERMS Electrolyte Gating, Spin Liquids, Complex Oxides, Correlated Electrons					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT UU	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON David Goldhaber-Gordon
a. REPORT UU	b. ABSTRACT UU	c. THIS PAGE UU			19b. TELEPHONE NUMBER 650-724-3709

Report Title

Final Report: STIR: Novel Electronic States by Gating Strongly Correlated Materials

ABSTRACT

Electrostatically modulating the carrier density of semiconductors, where the physics is relatively simple and well-understood, has long been the foundation for electronic devices. What if we could apply these techniques to a much broader range of materials? This short grant aimed at demonstrating such large potential modulations in correlated electron materials using a technique known as electrolyte gating. This plan built on my group's recent demonstration of electrolyte gating in Strontium Titanate, using an atomically thin hexagonal Boron Nitride barrier to prevent disorder and chemical modification of the surface of the Strontium Titanate during the electrolyte gating. During the course of this grant, we refined our exfoliation techniques and learned to apply thin hexagonal Boron Nitride to single crystals of materials expected to show some of the most exciting correlated electron behavior which could be modulated by gating: spin liquids (e.g. a layered Sodium Iridate compound) and multiferroics (e.g. Bismuth Ferrite). We did not complete the process of electrolyte gating such materials, but did make important progress on it.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received

Paper

TOTAL:

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received

Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Number of Presentations: 0.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received Paper

TOTAL:

Number of Manuscripts:

Books

Received Book

TOTAL:

Received Book Chapter

TOTAL:

Patents Submitted

Patents Awarded

Awards

Graduate Students

<u>NAME</u>	<u>PERCENT_SUPPORTED</u>
FTE Equivalent:	
Total Number:	

Names of Post Doctorates

<u>NAME</u>	<u>PERCENT_SUPPORTED</u>
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME

PERCENT SUPPORTED

FTE Equivalent:

Total Number:

Names of Under Graduate students supported

NAME

PERCENT SUPPORTED

FTE Equivalent:

Total Number:

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:..... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:..... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):..... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:..... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields: 0.00

Names of Personnel receiving masters degrees

NAME

Total Number:

Names of personnel receiving PHDs

NAME

Total Number:

Names of other research staff

NAME

PERCENT SUPPORTED

FTE Equivalent:

Total Number:

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

Technology Transfer

STIR: Novel Electronic States by Gating Strongly Correlated Materials

David Goldhaber-Gordon, Stanford University

W911NF1410375, Army Research Office

Electrostatically modulating the carrier density of semiconductors, where the physics is relatively simple and well-understood, has long been the foundation for electronic devices. What if we could apply these techniques to a much broader range of materials? Strongly-correlated materials, where the electrons behave collectively rather than as independent particles, have a much richer and less well-understood landscape of phases. The physics of strongly-correlated materials is at the heart of some of the most important current problems in condensed matter physics, and Army interest in these systems is reflected in heading 6.1.1 of the BAA. For example, electron interactions can turn materials that are expected to be metals into insulators. Advances in modern electronics already depend on systems of electrons that do not behave independently from one another. Applying field-effect gating techniques to modulate chemical potential could allow us to explore a broad range of strongly-correlated systems in a novel way.

In conventional electrostatic gating, the breakdown voltage of the oxide dielectric that separates the gate from the channel limits induced electron density changes to approximately 10^{13} cm^{-2} . This is sufficient to gate semiconducting materials, where the electronic bandgaps and charge carrier densities are small. Because energy scales in strongly-correlated systems are generally much higher, order-of-magnitude greater swings in potential or density are required to modify the electronic properties and tune through interesting phase transitions. Chemical doping of strongly-correlated systems can achieve these large density swings, and has led to remarkable phenomena.

This short grant aimed at demonstrating such large potential modulations in correlated electron materials using a technique known as electrolyte gating. This plan built on my group's recent demonstration of electrolyte gating in Strontium Titanate, using an atomically thin hexagonal Boron Nitride barrier to prevent disorder and chemical modification of the surface of the Strontium Titanate during the electrolyte gating. During the course of this grant, we refined our exfoliation techniques and learned to apply thin hexagonal Boron Nitride to single crystals of materials expected to show some of the most exciting correlated electron behavior which could be modulated by gating: spin liquids (e.g. a layered Sodium Iridate compound) and multiferroics (e.g. Bismuth Ferrite). The challenges involved in trying to do subsequent lithographic patterning on irregularly shaped, millimeter or smaller single crystals proved formidable, so we decided to fall back to electrolyte gating of insulating (small gap) single crystals and conductive films. While we were not able to electrolyte gate other complex oxides in the ~6 month run of the grant, we succeeded in electrolyte gating graphene, apparently without strong suppression of mobility. This offers the near-term prospect of a material with better room temperature conductivity than the best known conductors (silver and copper). This was not the main aim of the grant, and has still not been published, but is an important step

toward the target of gating a wide variety of materials without worrying about chemical compatibility and interaction between electrolyte and substrate, and without generating substantial disorder.

One graduate student was partly supported on the grant. He should graduate in the next 1.5 years. One researcher who had just finished undergraduate studies was also supported. He has been admitted to Ph.D. programs in Physics, largely based on research performed under this grant, and will likely attend one in the Fall.